Direct Air Capture of CO_2 and recycling CO_2 into Sustainable Aviation Fuels

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CAAFI

PRESENTED BY
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Anna is a professional engineer with over 15 years' experience bridging the gap between technology and business to overcome barriers to cleantech commercialization.

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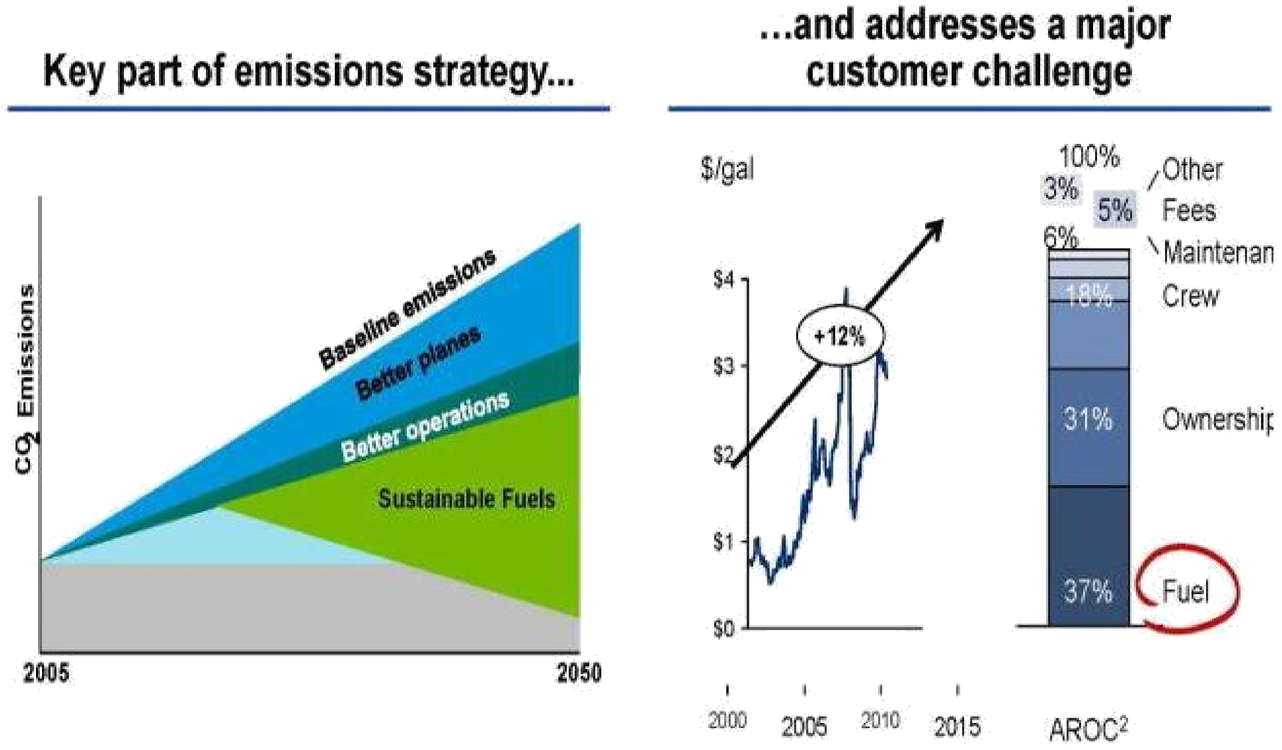
Ellen is Professor of Practice in the School of Molecular Sciences since 2012 with over 25 years experience in managing use-inspired, multi-disciplinary, and multi-organizational research, development and deployment of new technology for clean energy.

Future of Liquid Hydrocarbons and Aviation?



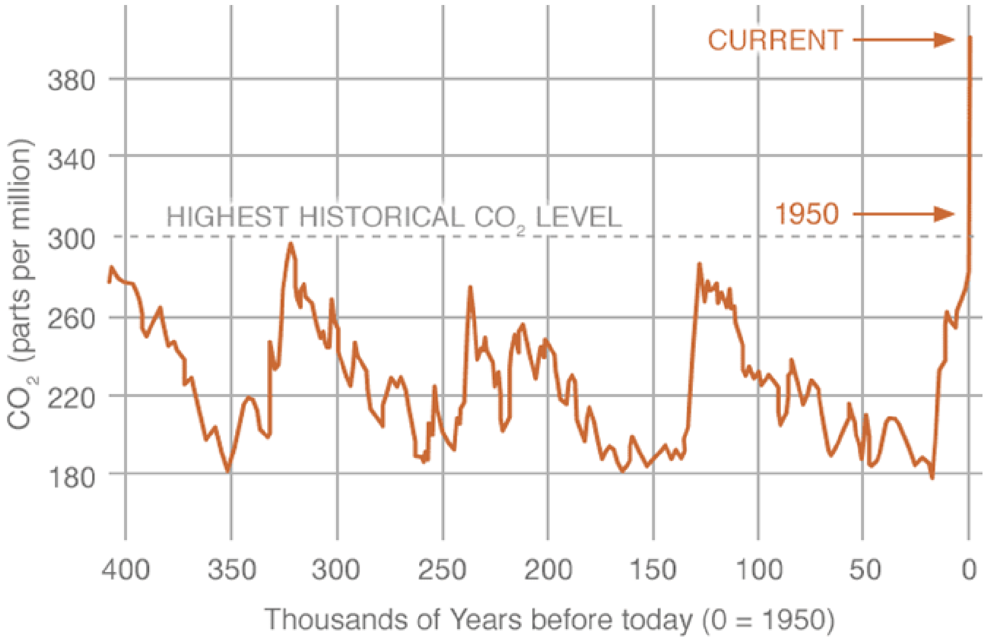
- Sustainable fuels and biofuels have been treated as synonymous
- Renewable synthetic fuels are a great opportunity to expand the portfolio of options, with few to effectively no scale limitations
- Solar fuels are complementary not competitive with biofuels
- Direct air capture (DAC) of CO_2 feedstock enables full de-carbonization of the fuel
- DAC also enables negative emissions offsets
- Need many “arrows in the quiver”

Low water, no arable land, land efficient, and price stability

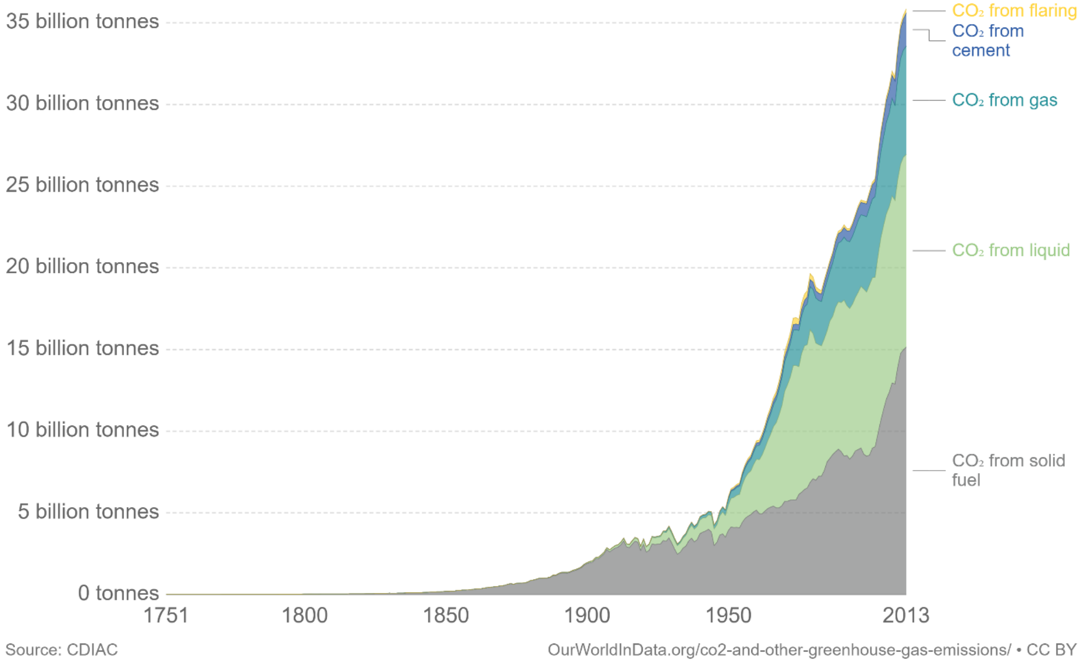
The Bathtub is Very Full and Still Filling Rapidly

CO_2 analysis shows that current levels are almost double the long-term average and growing faster than every before.

Atmospheric CO_2 Concentration

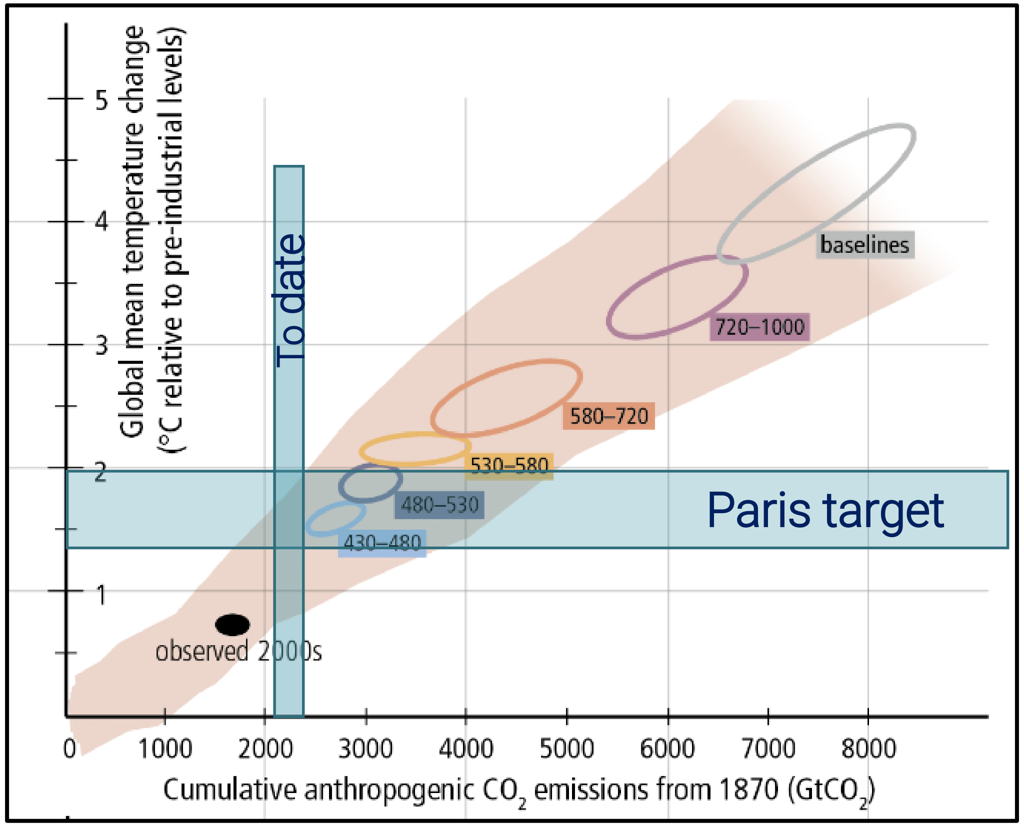


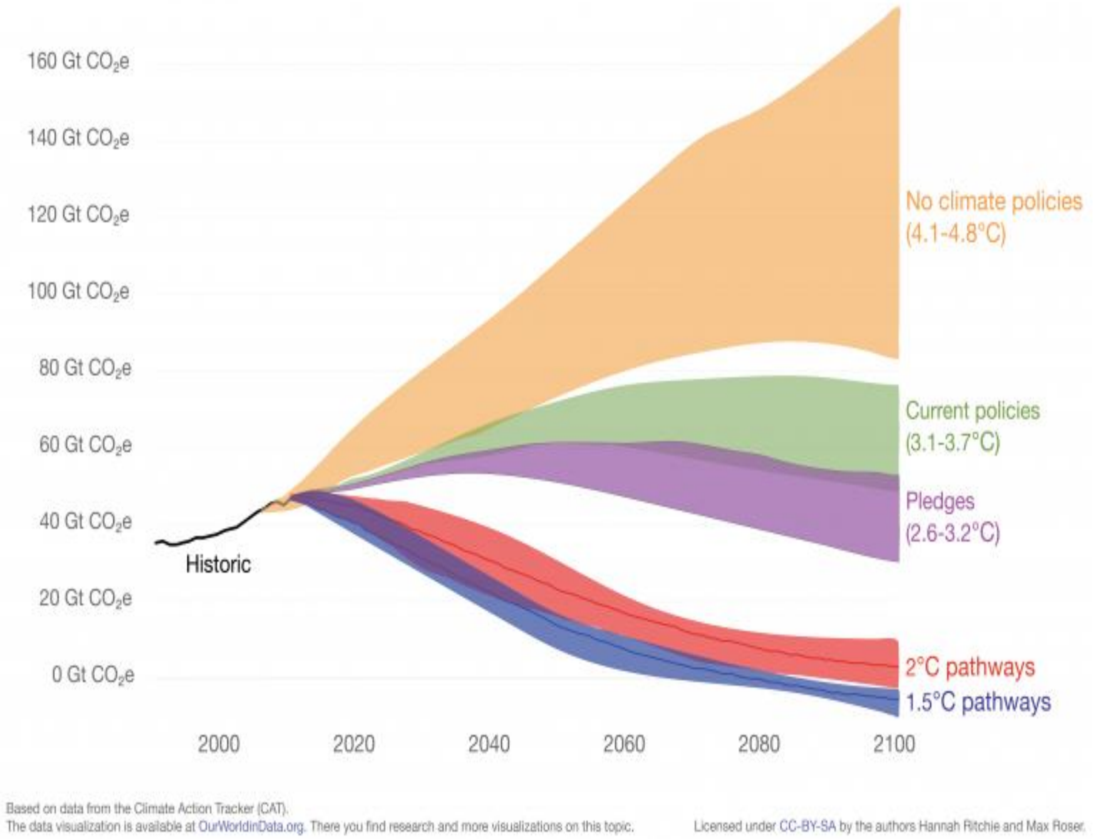
CO_2 Emissions by Source



Using a bathtub analogy, the CO_2 bathtub is much more full than normal (almost twice as full as the average over human history), and it is being filled faster than ever before.

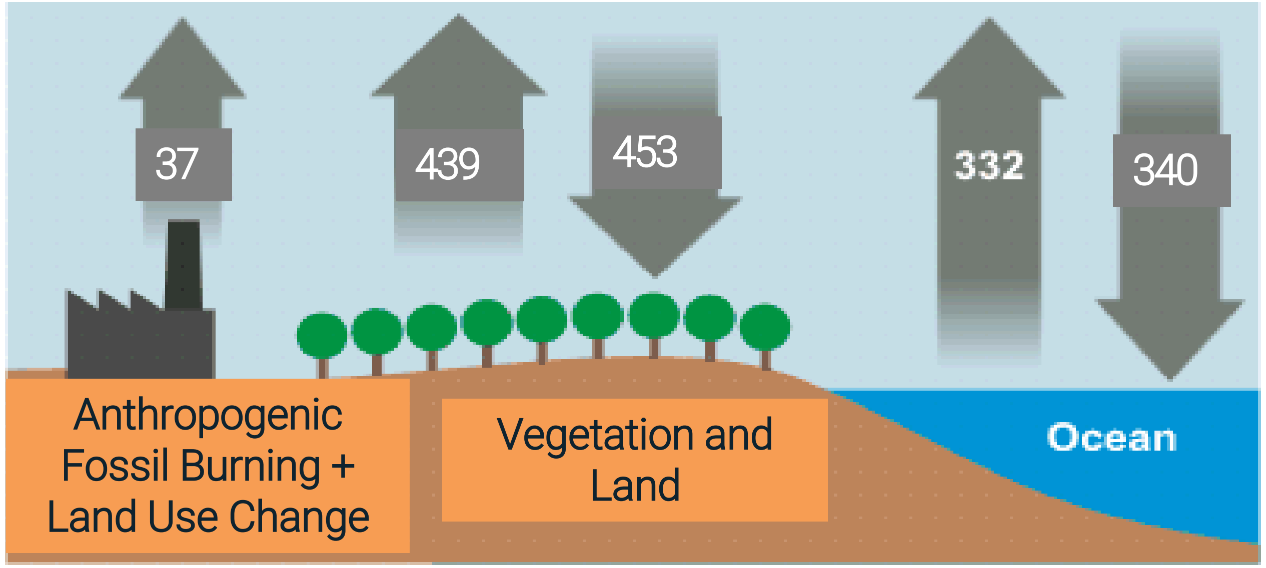
It is the Cumulative Emissions that Matter





The Carbon Budget is almost exhausted

Reducing atmospheric concentration of CO_2



Accounts for ~76% of GHG

Uptakes ~35%

Uptakes ~25%

- ~3100 $GtCO_2$ total in the atmosphere
  - Was ~ 2200 Gt pre-industrial
- Beyond ~3500 Gt is considered too much >450 ppmv
- Proven fossil reserves:
  - ~2800 Gt potential CO_2 emissions
  - Cumulative budget left ~400-900 $GtCO_2$

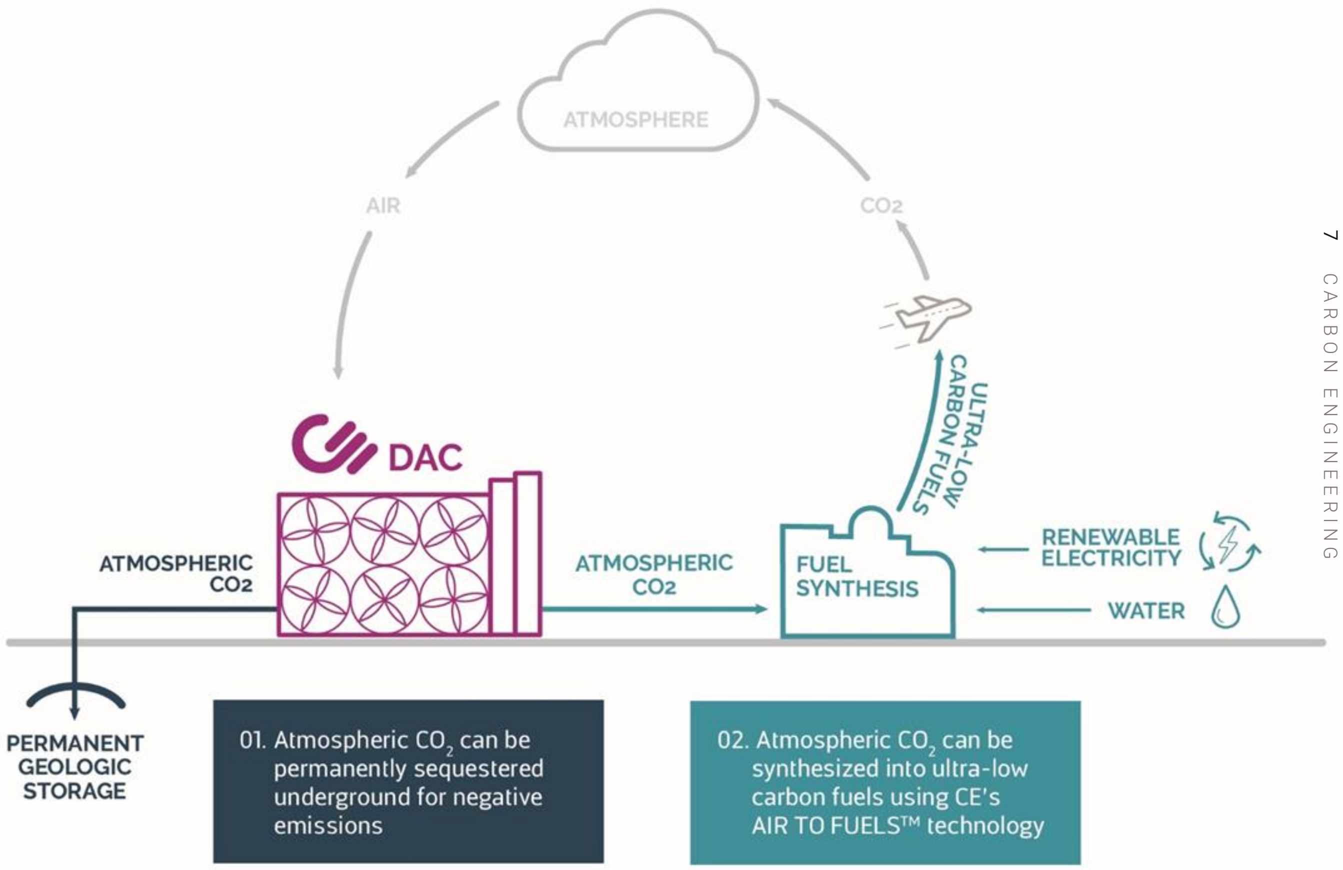
- Actively mine the excess CO_2 in the atmosphere as a resource and an option to deal with likely overshoot
- 500 Gt-CO_2 at \$2.5 per metric ton profit would be \$1.25T.

2040 ± 310 $GtCO_2$ cumulative emissions 1750-2011 → 880 ± 35 additional $GtCO_2$ in the atmosphere

Problem: Increasing CO_2 content in both the atmosphere and ocean

How do we keep the bathtub from overflowing?

- The United Nations Intergovernmental Panel on Climate Change (IPCC) has identified pathways to limit global warming caused by green house gases to 1.5° C. All pathways include:
  - very aggressive reduction in CO_2 emissions (turning down the taps of the bathtub)
  - large scale CO_2 removal (opening the drain of the bathtub).
- Carbon Engineering's mission is to mitigate climate change through mass scale deployment of two linked technologies:
  1. Direct Air Capture plants for CO_2 removal
  2. AIR TO FUELS plants for CO_2 reduction in transportation fuels



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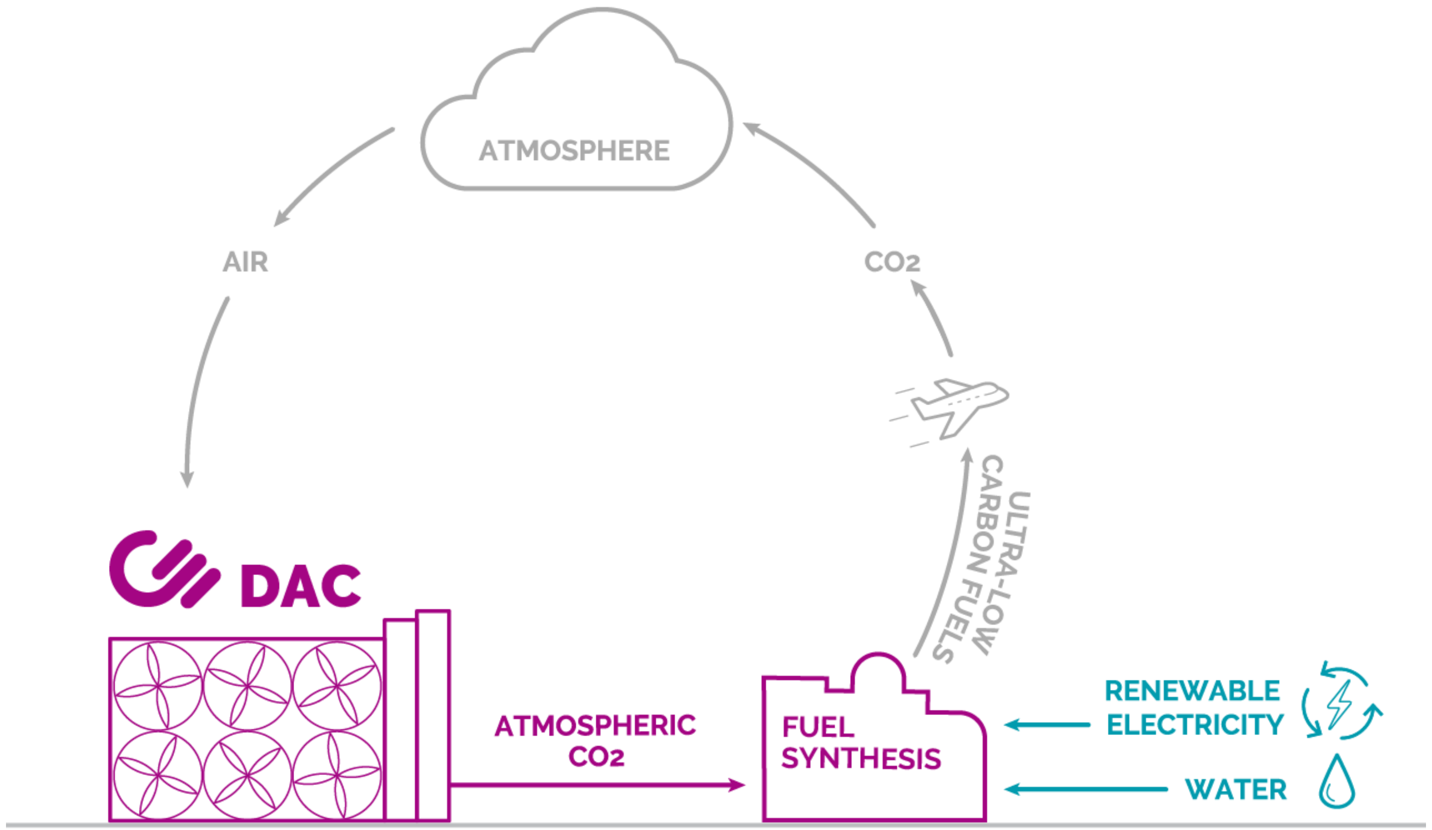
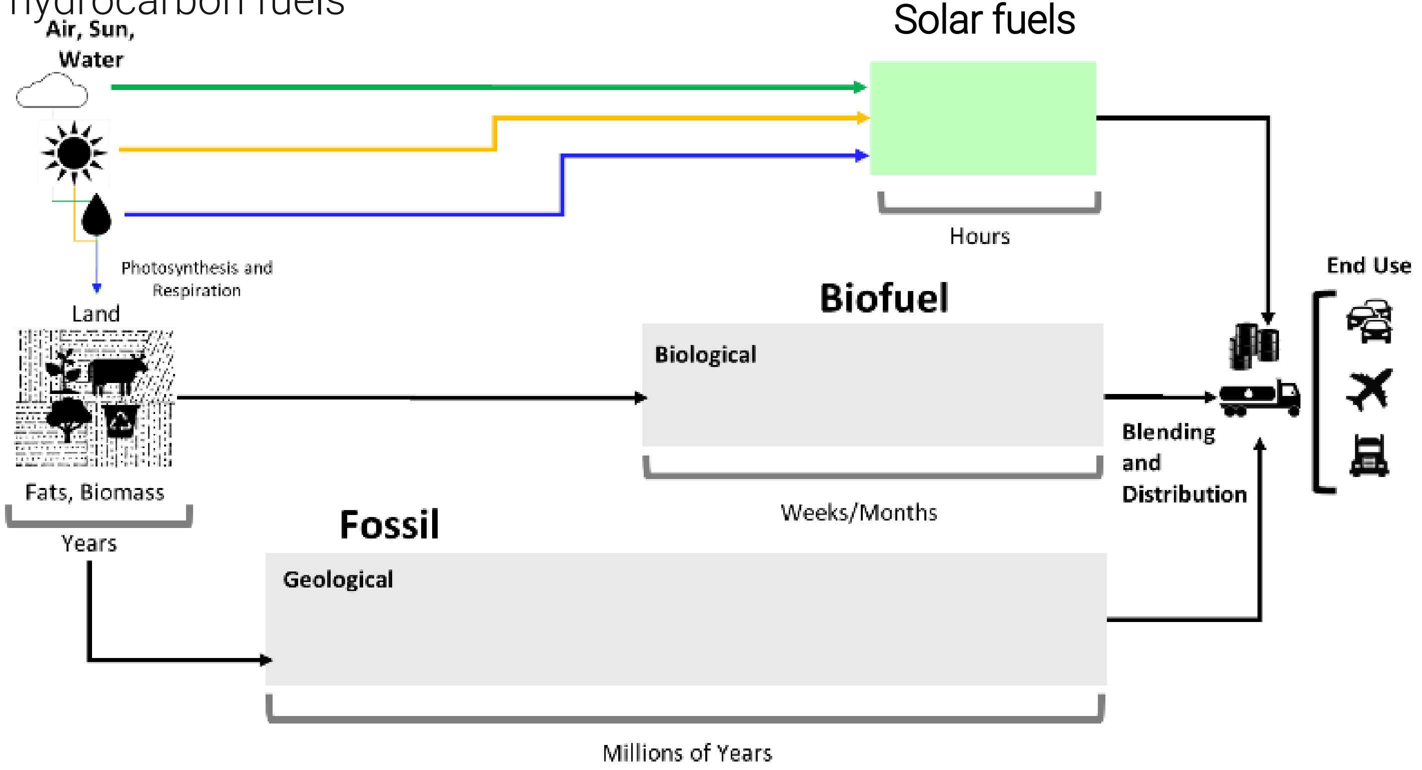
Scalable options for decarbonizing the heavy transportation sector.

DAC Enables Ultra-low Carbon Fuels



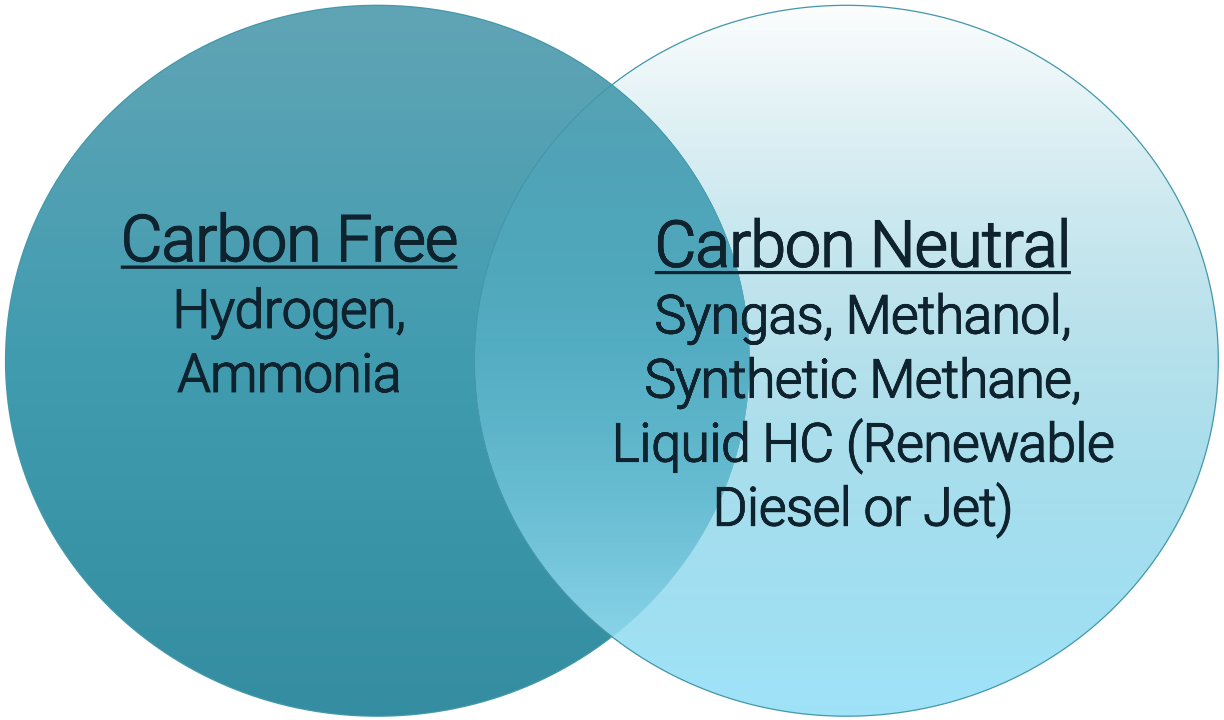
Solar Fuels Pathway Compared to Biofuels and Fossil Fuels

- All fuels begin with a common set of ingredients - air, sun and water – whether they are fossil, biofuels, or solar/electrofuels
- CE's AIR TO FUELS™ solution, one example of a solar/electrofuel, is a technological, rather than biological or geological approach to creating hydrocarbon fuels



> A2F can do within hours what took the Earth millions of years.

Alternative Fuels: Solar Fuels and Electro Fuels



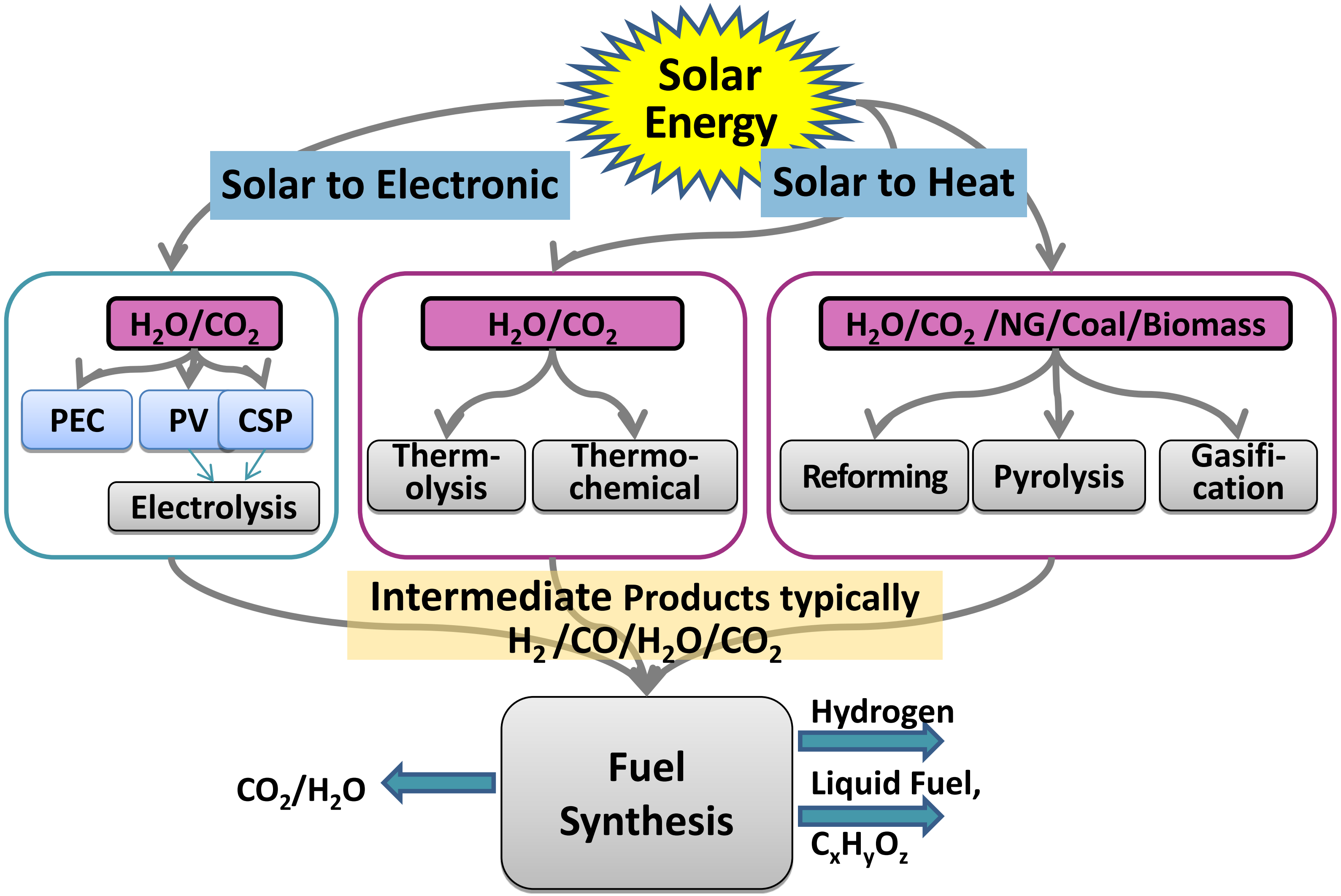
- Low (net) or zero carbon intensity
  - clean burning,
  - can be drop-in
  - can take advantage of trillions of dollars of infrastructure
- Based on the sun (scalable resource) but not on photosynthesis
  - or any carbon neutral primary energy source
- Alternative to nature's means to store the sun's energy in chemical bonds

Solar & Electro Fuel pathways have the potential for relatively High efficiency

Significant scale, Affordable cost, and Flexible products

Low water, No arable land, Land efficient, Price stability, Democratic

Many Synthetic Pathways: Many Arrows in the Quiver



Pathways

- Bio-chemical
- Photo-(Electro)-Chemical
  - Dye-Sensitized
  - Band Gap Excitation
  - Artificial Photosynthesis
- Thermo-Chemical
  - 2-Step Metal Oxide
  - Hybrid Sulfur
- Electro-Chemical
- Catalytic
- Combinations
- Etc.

A chemist's dream

Deep Skepticism on Direct Air Capture is Melting

- Carbon Engineering, Calgary, Canada Based
  - Aqueous based
- Global Thermostat, California, USA Based
  - Amine based sorbent and low temperature steam
- Climeworks, Zurich, Switzerland Based
  - Amine based sorbent, vacuum pumping
- Infinitree (formerly Kilimanjaro)
  - Humidity Swing – targeting Greenhouses
- Silicon Kingdom Holdings, Ireland Based
  - Humidity swing, passive
- Prometheus, founded 2018
  - CO_2 to Alcohol to Jet at room temperature

Advantage/Disadvantage of Air Capture vs. Point Sources

Advantages:

- Source essentially infinite: 3 trillion metric tons
- Distribution: Anywhere
  - Readily sited to use a pure renewable source
  - CO_2 captured can equal CO_2 avoided
  - Readily sited for point of consumption (limits compression and transportation costs
- Capture Temperature: Ambient
  - Favors exothermic capture
  - Don't have to manage heat removal
- Source contaminants: Cleaner than most point sources
- Source Handling
  - Can use some natural air movement or "engineered" flows
  - Fans, updraft towers, passive
  - Pressure drop is inherently much lower

Disadvantages:

- Source very diffuse
  - C ~400 ppmv ; factor of 300 less than from coal
  - Must process large amount of the source
  - Energy to move that source can be appreciable
- Minimum work to separate
  - Relatively slow function of C (log)
  - e.g. compare 50% air capture at ambient to 90% point source at 40°C – ratio is 2.8 x << 300 x
- Competition with binding water – much more water in the air than CO_2

More advantages than disadvantages – it is not evident that from a systems perspective that direct air capture is less cost effective than from point source

DAC Has Many Advantages Compared to Point Source

This can be essentially zero

Integrate with heat available from downstream processing and with Renewable Energy

Cleaner and Lower Temperature

Less harsh conditions, longer cycle times, longer lifetime

Compression minimized

Transport essentially eliminated

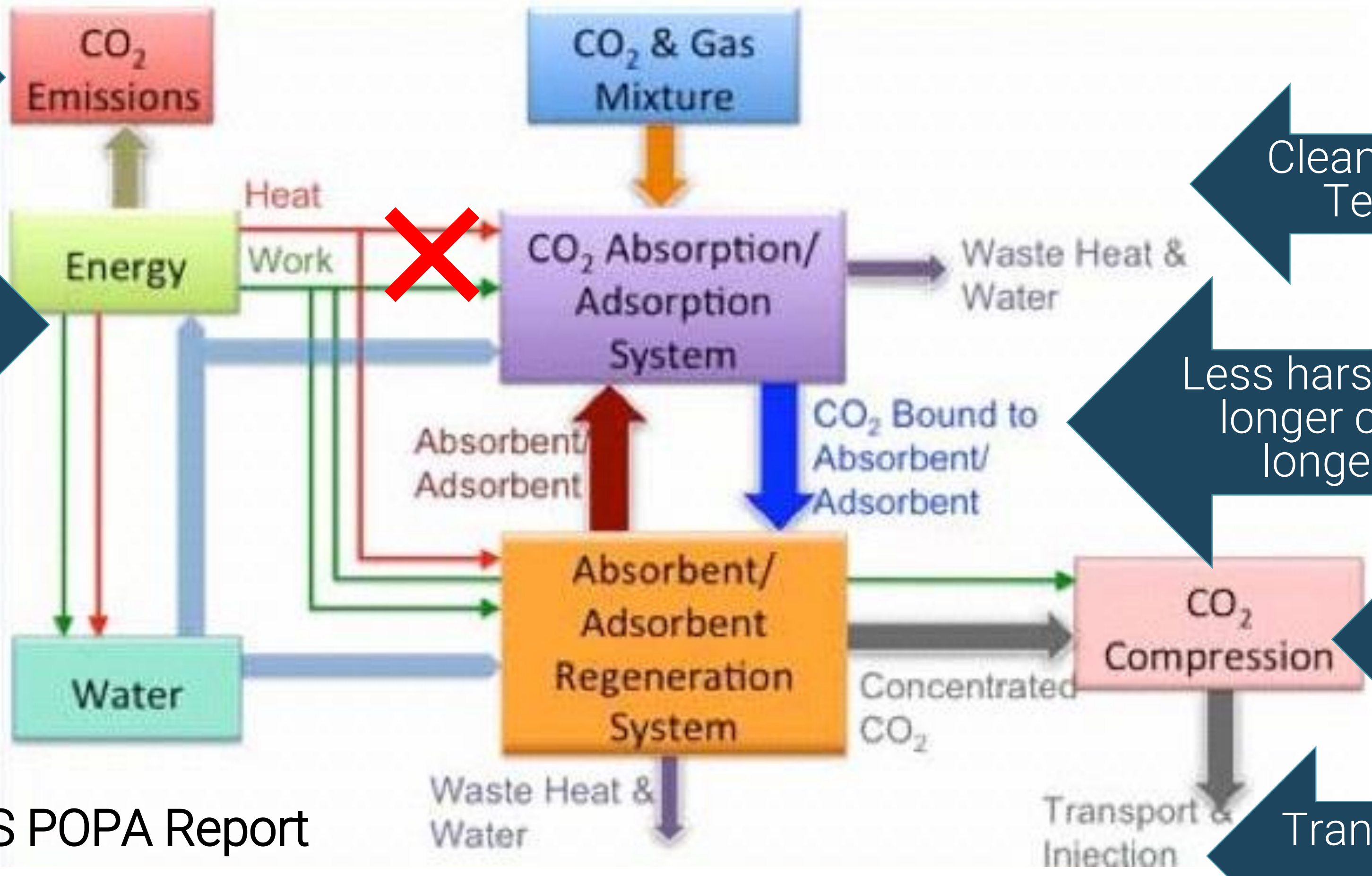
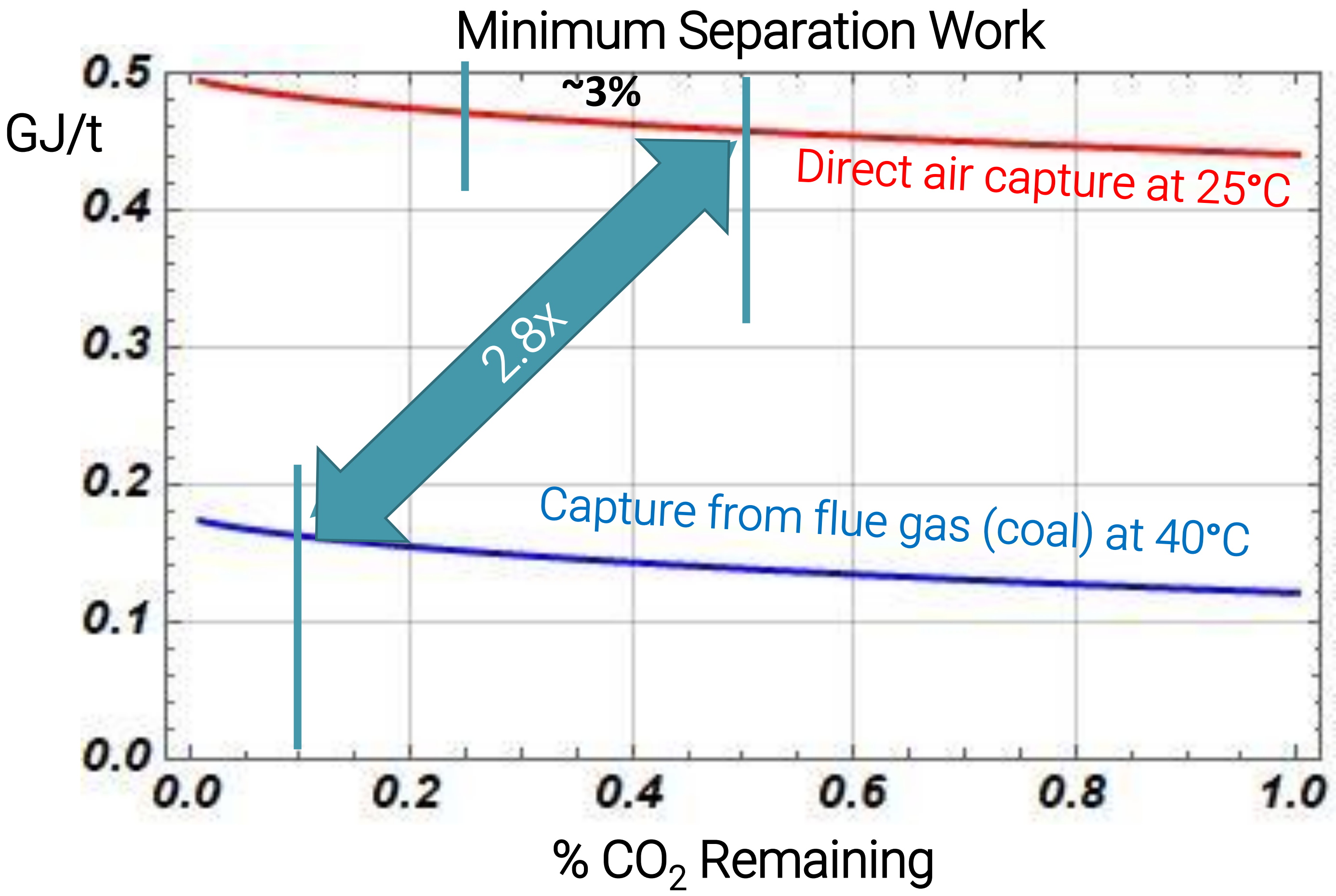


Fig 2.1 from the APS POPA Report

For 10 Gt per year, <u>minimum</u> energy is ~144 GW (0.45 MJ/kg);

Compare global energy 18 TW and 32.6 Gt/year CO_2 emissions (17.4 MJ/kg)

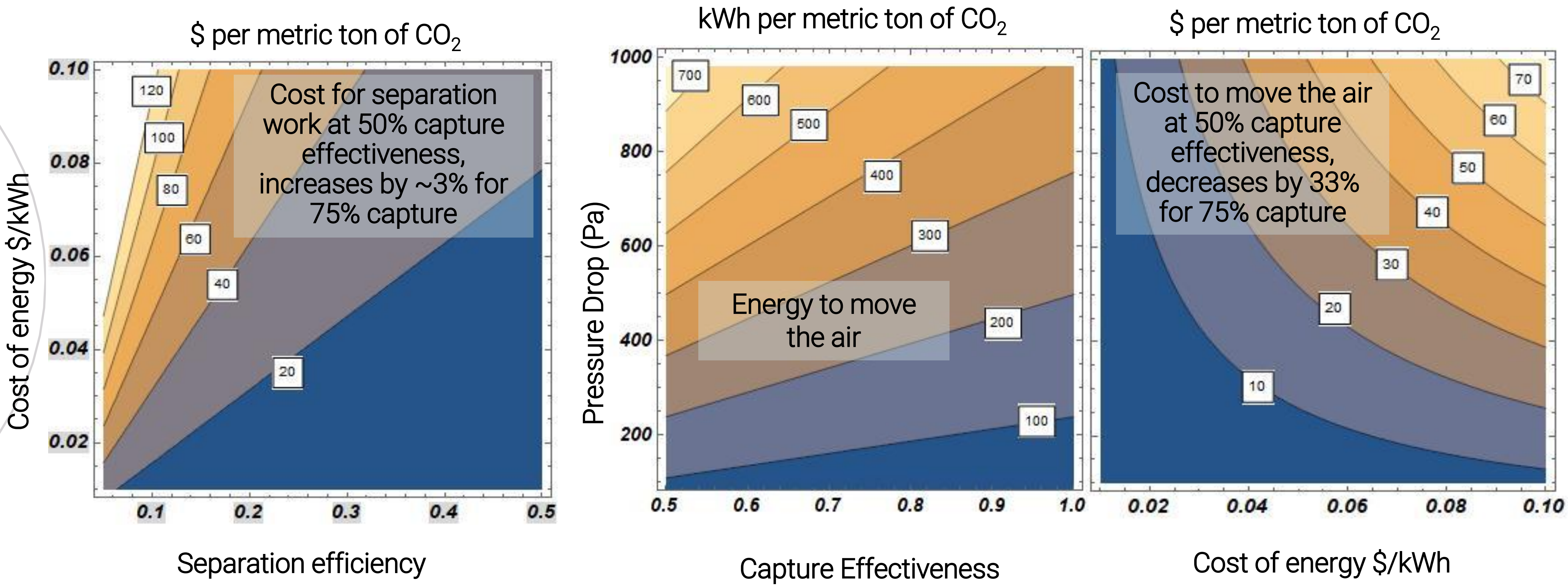
Air Capture Passes the “Thermodynamic Hurdle”



- 8.5 kg CO_2 per gallon Jet Fuel
- 82.5 B gallon/year(2012)
  - ~700 Mt/year CO_2
- Minimum separation work
  - 10.2 GW; Could be ~20x or ~200 GW
  - Separation efficiency challenge
- 14.4 GJ Jet Fuel per metric ton CO_2
  - 320 GW of fuel
- If 10% efficiency sunlight to fuel synthesis
  - 3.2 TW (~4M acres of collectors, < 0.2 % U.S.)

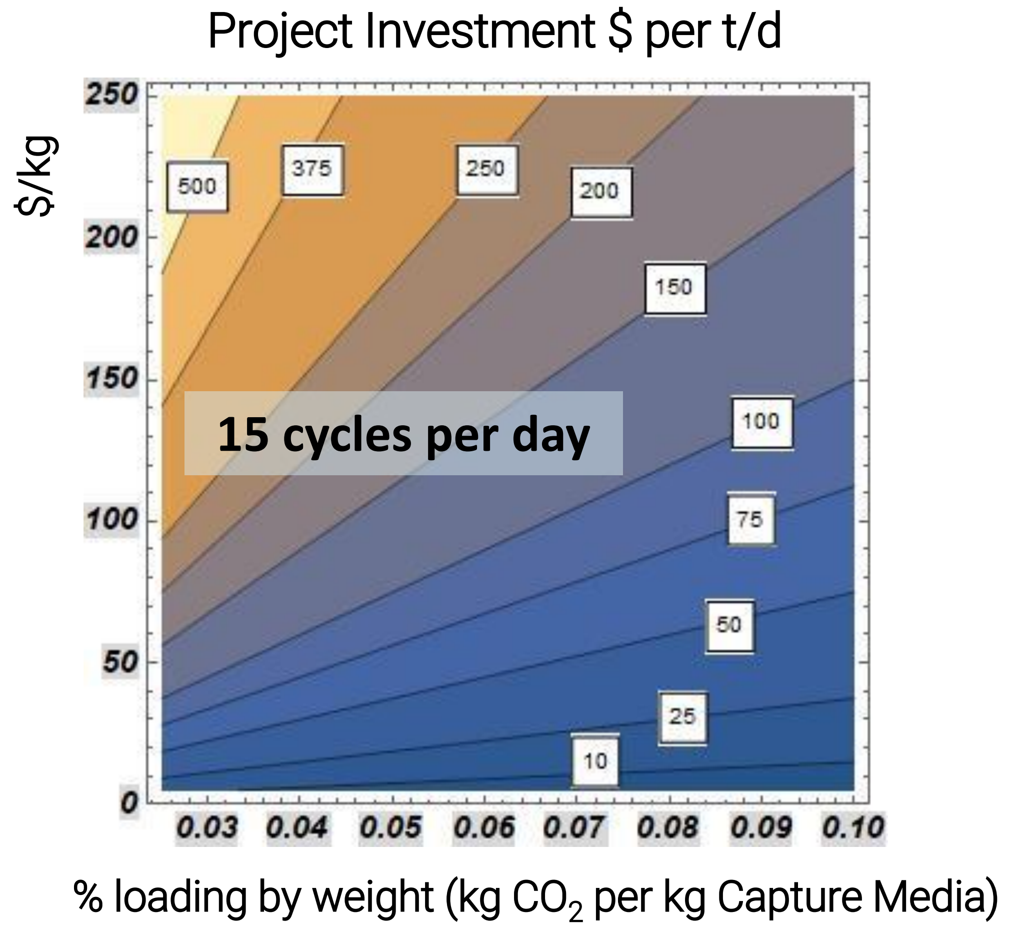
Separation work is a small fraction of total energy to make fuel < 10%

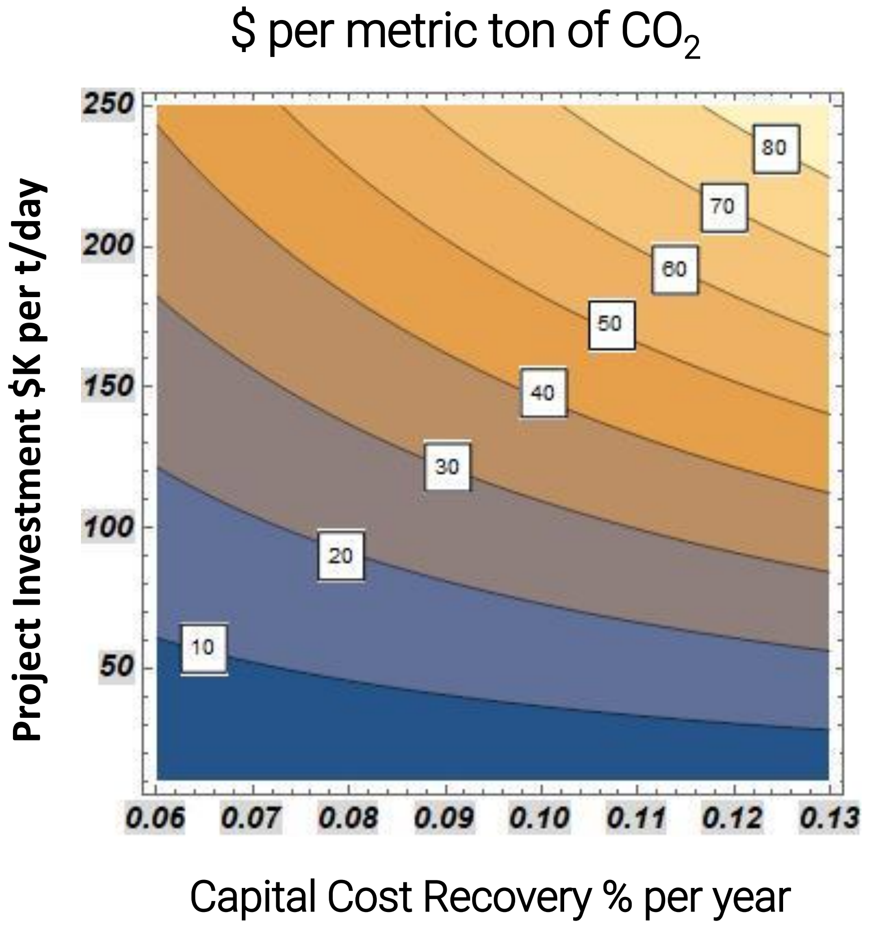
What About the Cost of Energy: Fundamentals for Sorbent-Based



Contactor design and approach to moving the air matters – key parameters are the capture effectiveness, the pressure drop, and the cost per unit energy

What About the Cost of Capital: Sorbent-Based

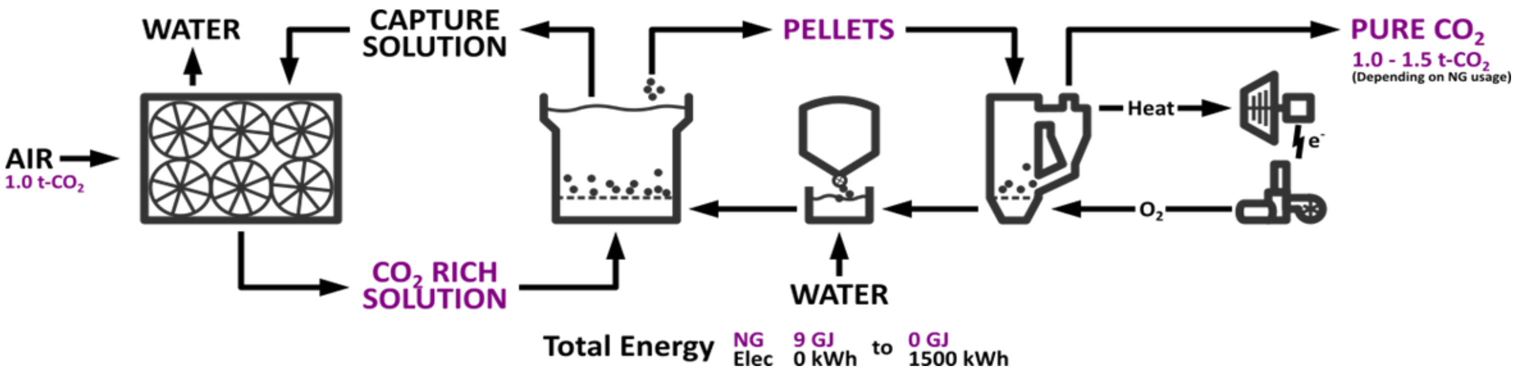




Cycle time, lifetime, and financial terms for the investment are all important

Expect first of a kind >> Nth of a kind; Expect learning curves will decrease cost

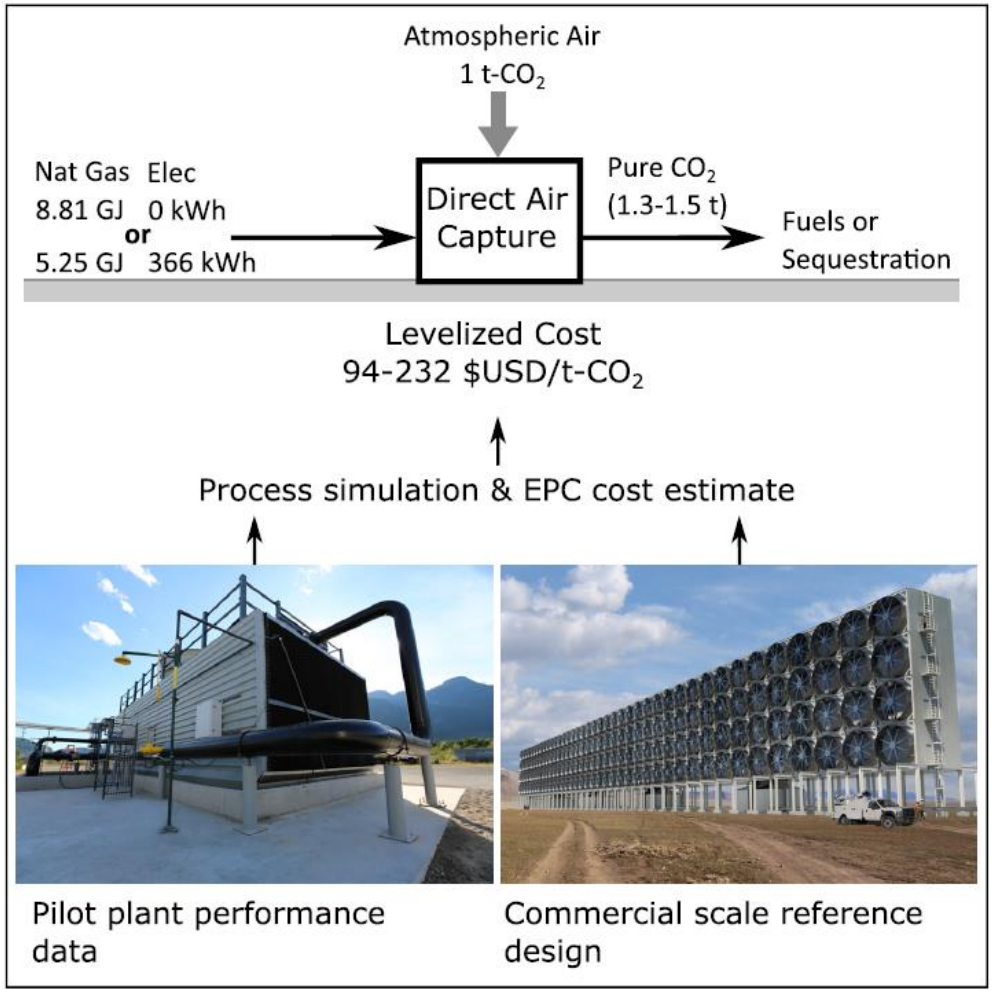
CE's Direct Air Capture of Atmospheric CO_2



Industrially Scalable	A combination of pre-existing technologies have been adapted and combined with patented innovations, and proprietary know-how, which has reduced scale up risk and improved cost estimation.
Closed Chemical Cycle	Non-volatile non-toxic chemical process, meets environmental health and safety standards.
Freedom of Location	Plants can be located where economics are optimum, to take advantage of low cost local energy or proximity to demand center.

CE has been developing Direct Air Capture technology since 2009, and has proven the technology through successive prototype and pilot demonstrations

CE Techno-Economic Analysis



- CE published comprehensive technoeconomic analysis of our DAC process in the journal Joule, June 2018
- Included detailed engineering and cost analysis for a 1 Mt-CO_2/year direct air capture plant
- Levelized costs, including financing, of \$94-232/t-CO_2
- Full mass and energy balance with pilot plant data for each unit operation included

CE Techno-Economic Analysis (1)

Scenario	Gas Input[a] (GJ/t-CO_2)	Electricity Input[a] (kWh/t-CO_2)	C-Gas/C-Air	Capital $ per t-CO_2/year	O&M[b] ($/t-$CO_2$)	Levelized[a] ($/t-$CO_2$) CRF[c]	
						7.5%	12.5%
A: Baseline: gas fired → 15 MPa CO_2 output	8.81	0	0.48	1,146	42	168	232
B: Baseline with N[th] plant financials	8.81	0	0.48	793	30	126	170
C: Gas and electricity input → 15 MPa CO_2 output	5.25	366	0.30	694	26	113–124	152–163
D: Gas and electricity input → 0.1 MPa CO_2 output assuming zero cost O_2	5.25	77	0.30	609	23	94–97	128–130

[a]Gas and electrical inputs as well as levelized cost are all per ton CO_2 capture from the atmosphere.
[b]Non-energy O&M expressed as fixed per unit of capacity with variable costs including cost of make-up streams included and converted equivalent fixed costs using 90% utilization.
[c]CRF is the average capital recovery factor defined in the section on Process Economics. Calculations assume NG at 3.5 $/GJ and a 90% utilization. For the C and D variants levelized costs are shown as a range using electricity at 30 and 60 $/MWhr.

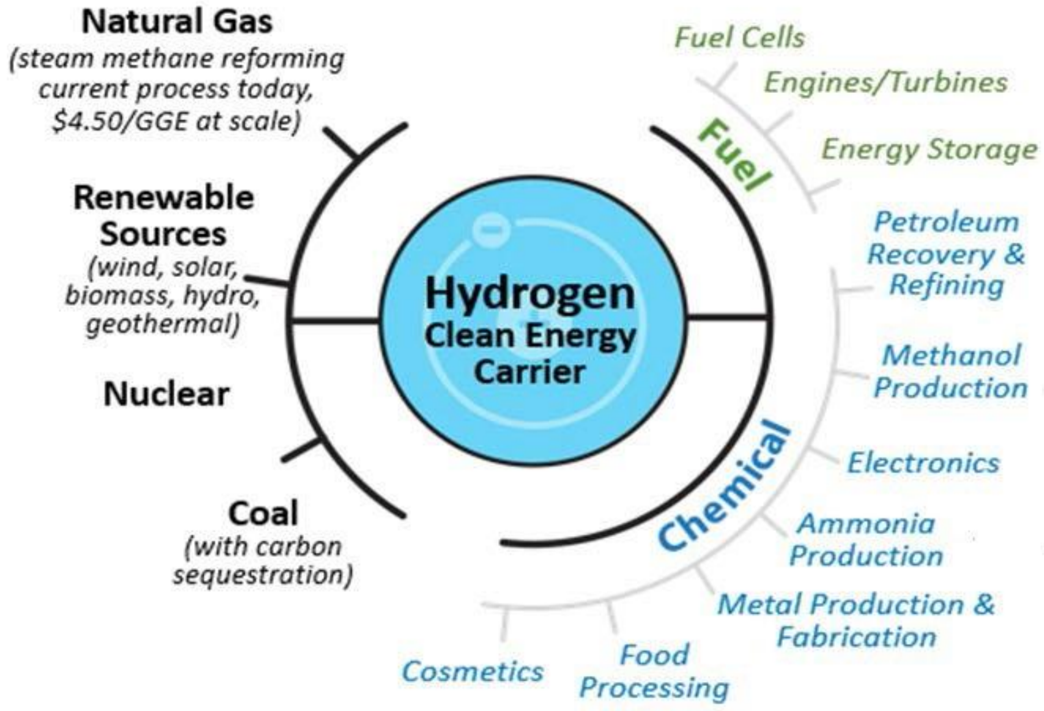
https://www.cell.com/joule/pdf/S2542-4351(18)30225-3.pdf

Hydrogen: A Clean, Flexible Energy Carrier

- 10M metric tons per year produced today
- Energy carrier – can deliver or store energy
- Petroleum and fertilizer largest uses today
- Transportation fuels and utilities are emerging markets
- Alternative reductant to coal, e.g., to make steel
- Production pathways
  - Steam methane reforming (could capture CO_2)
  - High and low temperature electrolysis
  - Direct Solar Water splitting: Photo-electro-chemical or Solar thermochemical
  - Biological or thermochemical biomass gasification with WGS (could capture CO_2)
- Can make CO from $H_2 + CO_2 \rightarrow CO + H_2O$

Diverse domestic sources can be used to produce H_2

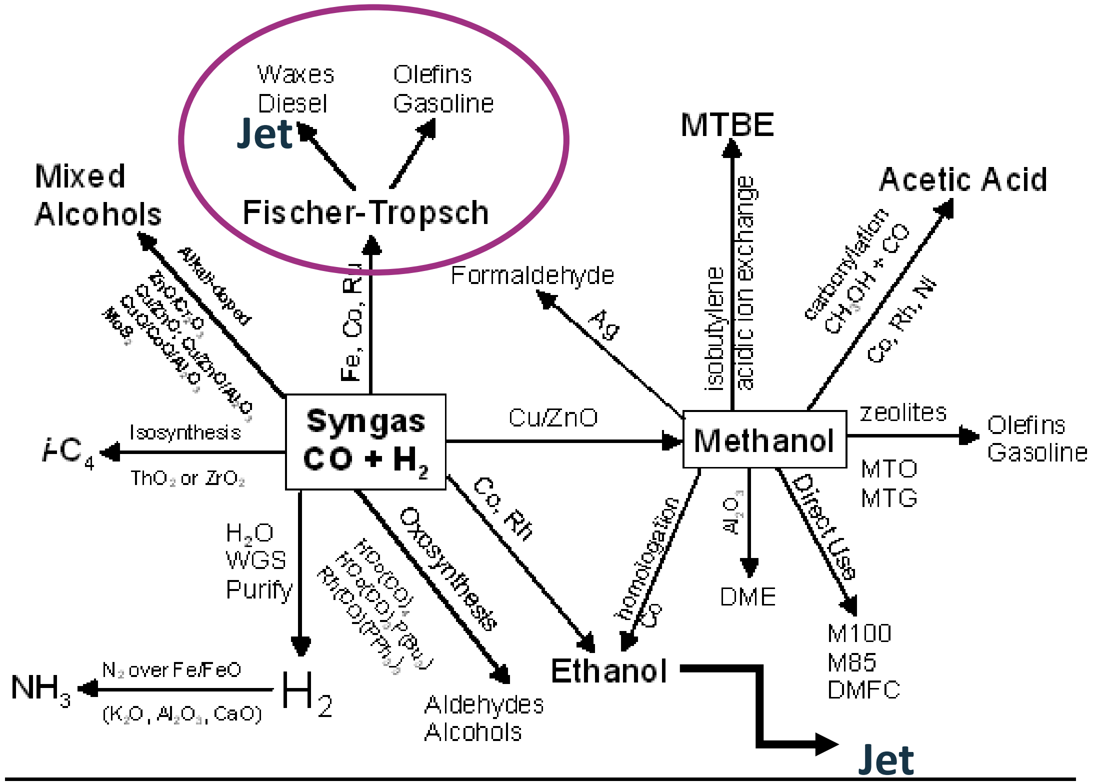
Many applications rely on or could benefit from H_2



Hydrogen is a versatile, carbon free, and effective energy carrier:

Multiple roles in the energy transition towards sustainability

The Advantage of Producing Syngas (CO and H_2)

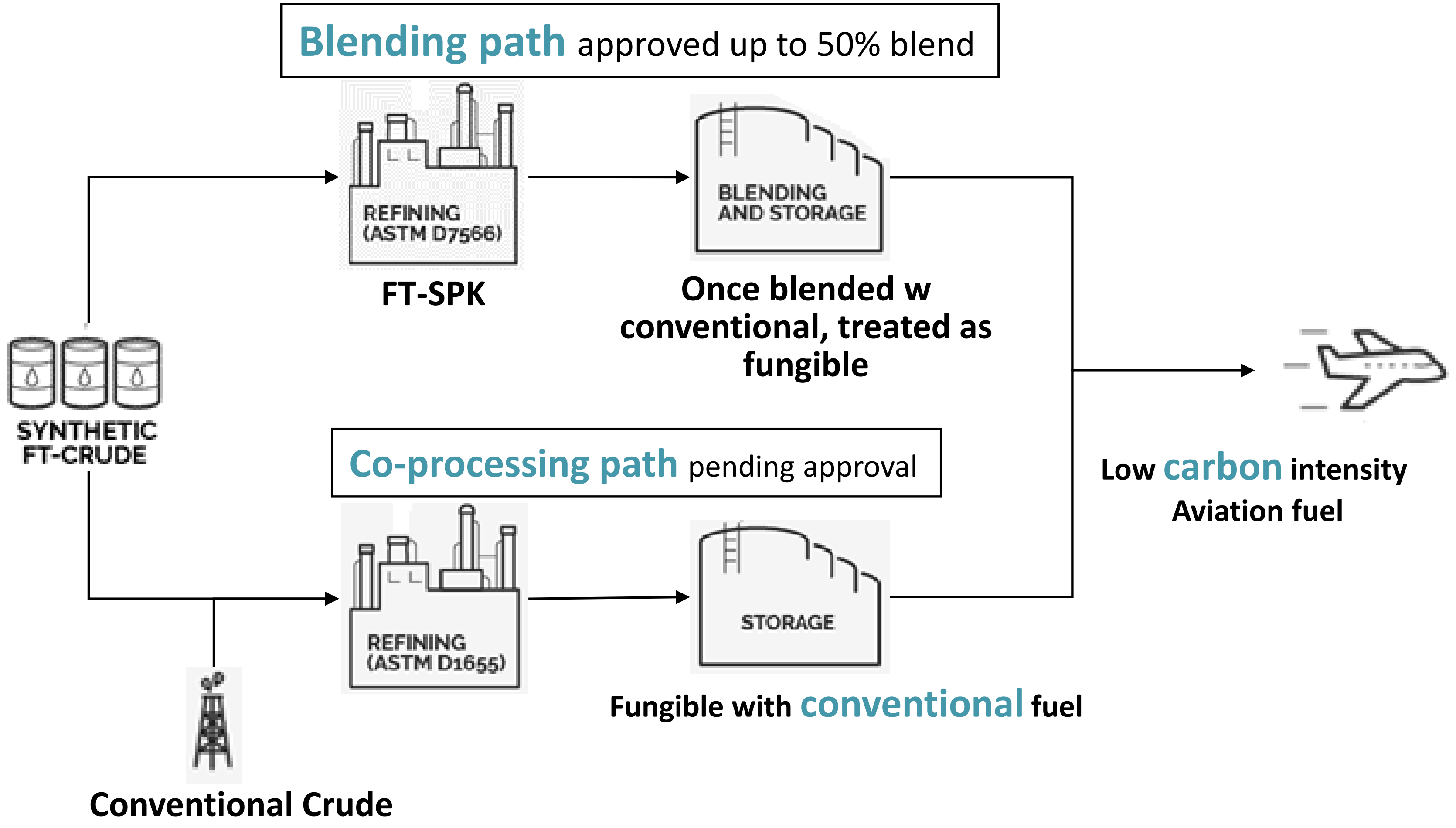


Source: P.L. Spath and D.C. Dayton, Preliminary screening—technical and economic assessment of synthesis gas to fuels and chemicals with emphasis on the potential for biomas-derived syngas, National Renewable Energy Laboratory, NREL/TP-510-34929, December, 2003.

- Universal intermediate
- Unite fossil and biomass with direct solar technologies
  - Bridge old energy to new energy
  - Make more product for the same feedstock – no process CO_2
- Directly splitting water and can also directly split CO_2
  - Aim for ~2:1 H_2:CO

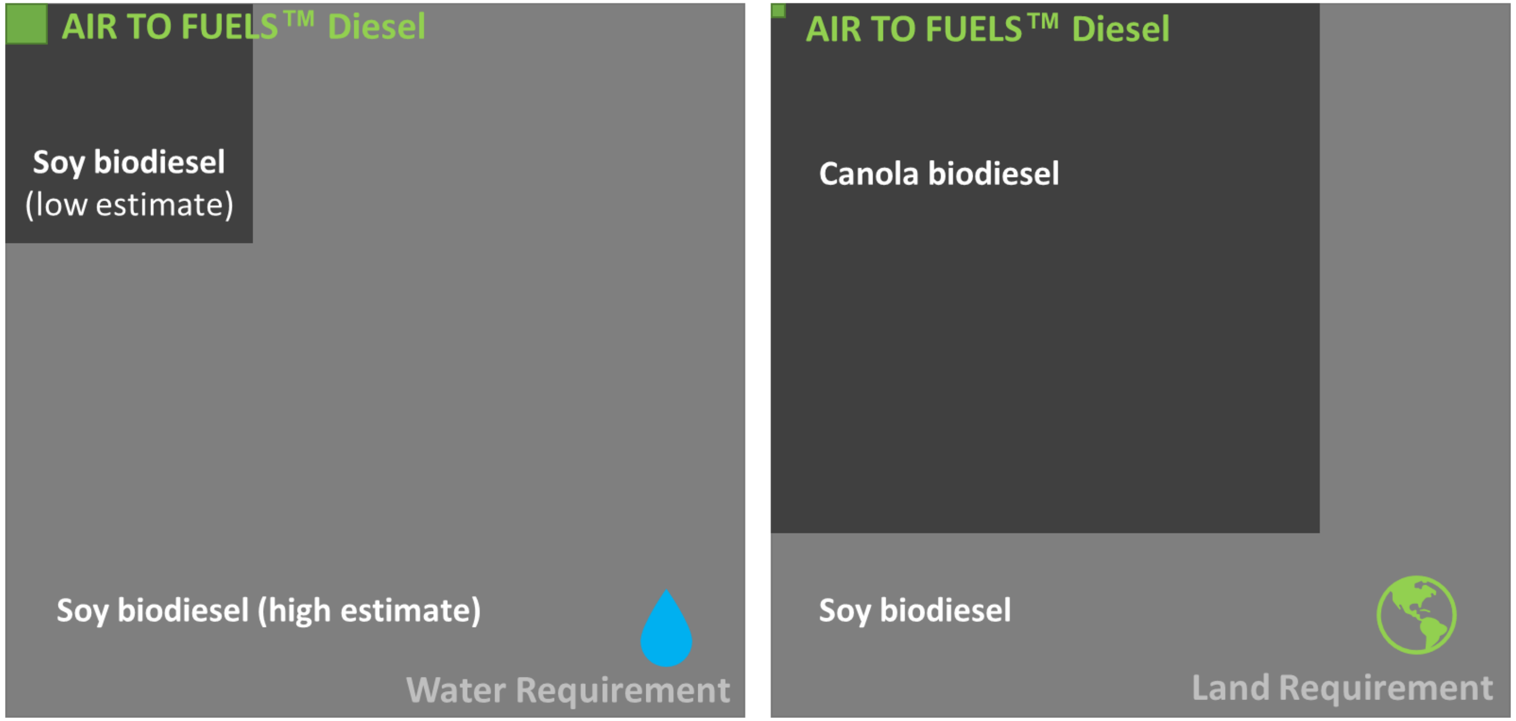
Can aim to achieve high carbon atom efficiency and to enable a smooth transition

From FT Liquids to Sustainable Aviation Jet Fuel



FT Liquids to SAJF already approved under ASTM

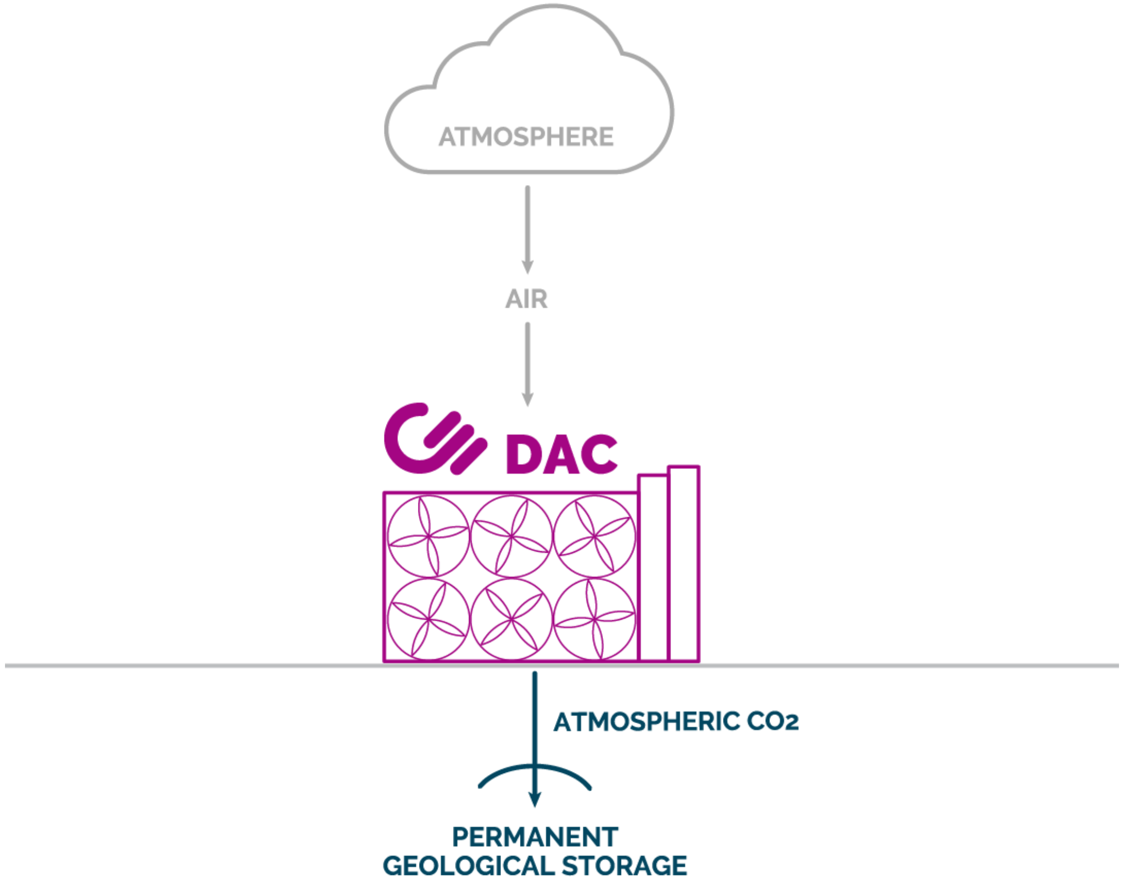
Land and Water Use Compared to Biofuels



~0.04%-0.06% land and ~0.3%-3% fresh water requirements vs. soy biodiesel

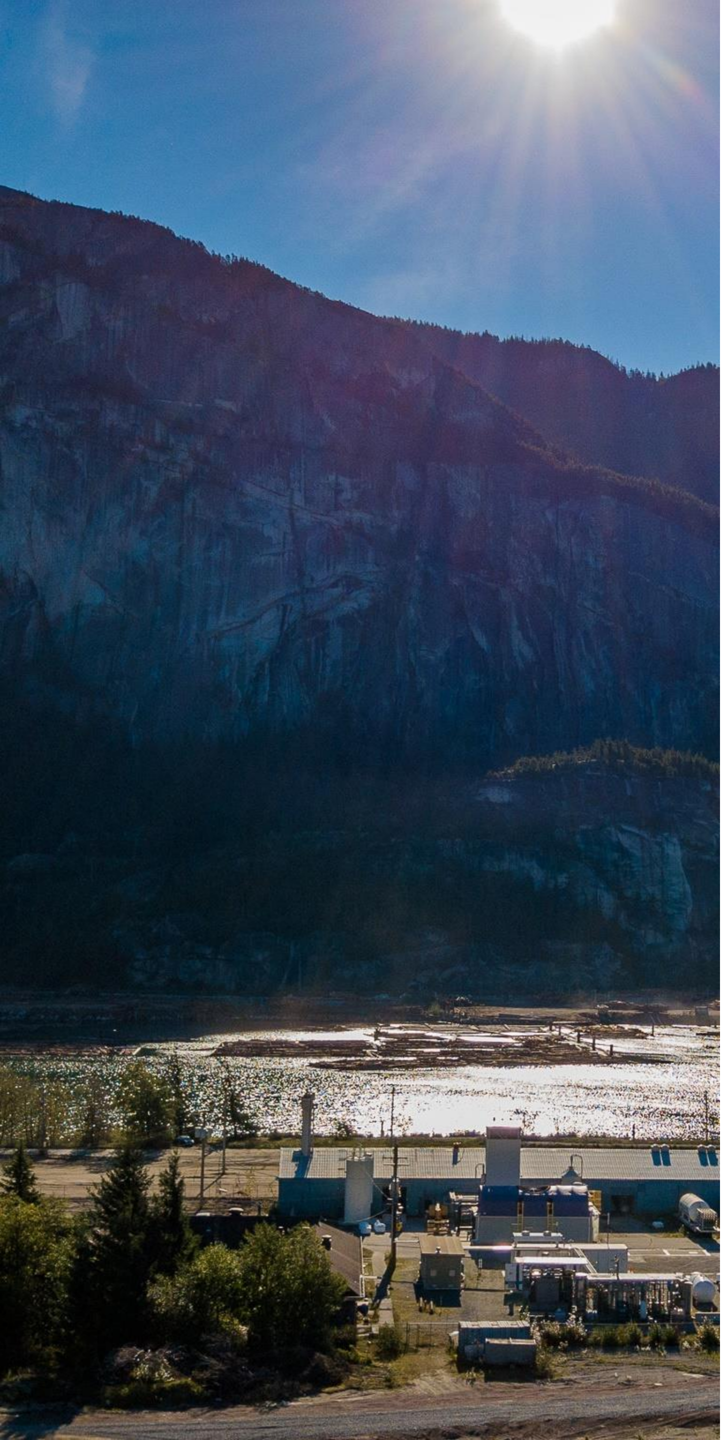
> Another tool in the toolbox as we look towards decarbonizing aviation

DAC Enables Negative Emissions



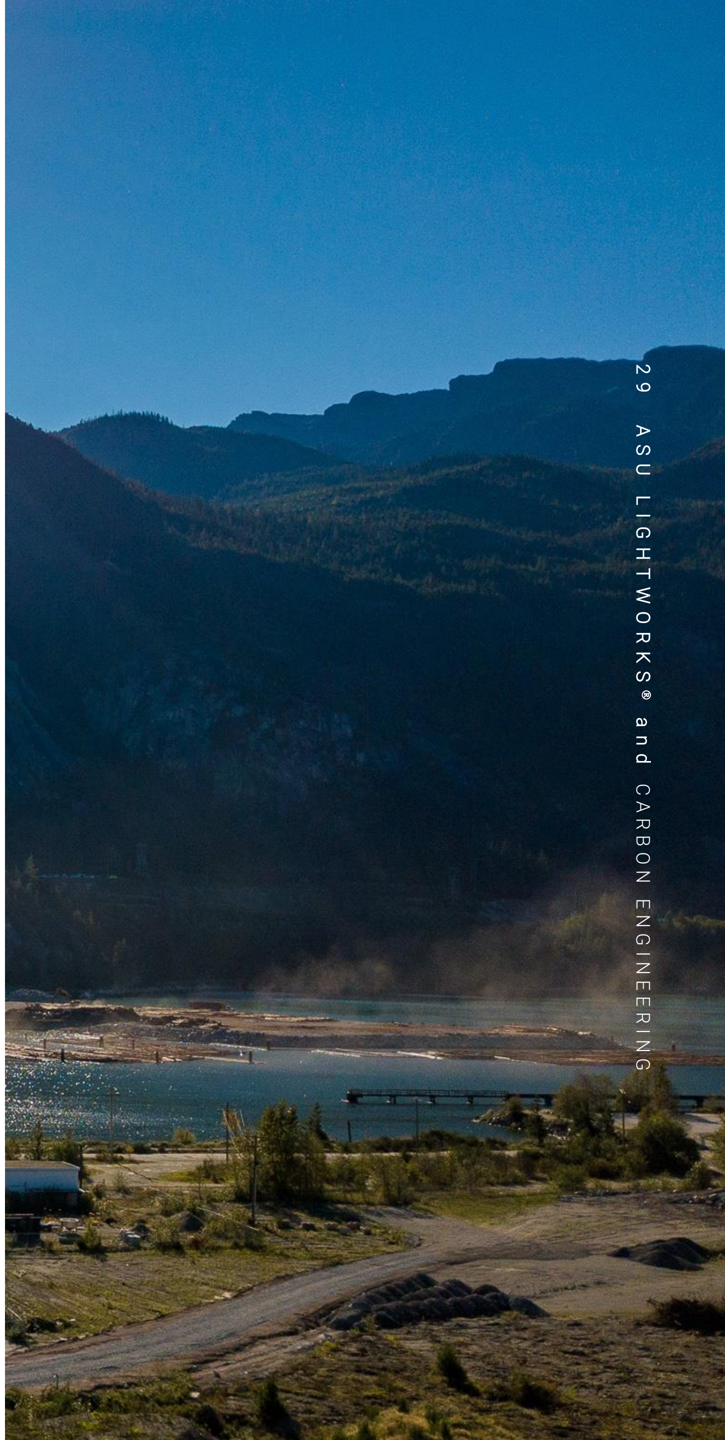
Path Forward

- Direct Air Capture is an essential tool for decarbonization
- Two significant new tools:
    - Highly scalable ultra low carbon fuels
    - Large scale atmospheric carbon removal
- Front end engineering commencing for CE's first commercial plant in 2019
- CE is actively seeking partners to help accelerate global deployment



Frequently Asked Questions Addressed Some Not All

- How cheap can the process eventually get?
- Why capture from air when it should be much easier to capture from concentrated sources?
- How much will it add to energy demand?
- Is it a moral hazard – excuse to continue to emit and count on to cleaning it up in the future?
- What kinds of businesses can startups build around the ventures?
- Will there ever be big enough markets for all the carbon dioxide we’d need to capture to meaningfully reduce climate risks?



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